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Insights from nitrogen compounds in gas oils highlighted by high-resolution Fourier transform mass spectrometry

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ABSTRACT: 23 gas oil samples from different origins were analyzed in positive and negative ion modes by electrospray ionization Fourier transform ion cyclotron resonance mass spectrometry (ESI(+/-)-FT-ICR MS). Sample ionization and ion transfer conditions were first optimized using Design of Experiment approach. Advanced characterization of basic and neutral nitrogen compounds in these samples was then performed through ESI(+/-)-FT-ICR MS analysis. A good repeatability was observed from the analysis of six replicates for each gas oil sample. Significant differences in molecular composition were spotted between the gas oils, either considering identified heteroatomic classes or within nitrogen families and were later correlated to samples macroscopic properties. The evolution of nitrogen relative intensities for one feed and two corresponding effluents has also been studied to monitor hydrotreatment reaction pathways towards aromaticity and alkylation levels evolutions.

Atmospheric distillation of crude oil produces several cuts including gas, gasoline, kerosene and gas oil (GO cut also called Straight Run Gas Oil, SRGO) with proportions depending on their origins¹. There is an increasing demand for light and middle distillates from gasoline to gas oils which does not go hand in hand with increasingly heavy conventional crudes². Thus, new challenges in refinery now lie in improving processes to transform heavy crude oils such as vacuum residues (VR) or vacuum gas oils (VGO) into lighter products.

The two main types of conversion processes used for gas oils production are: (i) thermal cracking-type such as coking processes that convert the VR into coker gas oils (GOCK) and (ii) catalytic cracking such as fluid catalytic cracking (FCC) which produces Light Cycle Oil (LCO) gas oils³. Similarly, VR hydrocracking can produce several types of gas oils depending on the technology used such as ebullated bed reactor (EBGO) or fixed bed reactor (FBGO). Hydrocracking (HCK) can be applied to VGO feedstocks leading to high-quality gas oils containing low sulfur and nitrogen contents. In comparison, the gas oils obtained by the conversion processes mentioned earlier are low-quality ones because of their high content of sulfur and nitrogen. Depending on the process employed for gas oils production, the gas oils have very different characteristics which impact their reactivity in the hydrotreating (HDT) processes.

Gas oil hydrotreatment is a key process in modern refineries in view of new specifications for sulfur content in gas oils products which are becoming increasingly stringent⁴. In the HDT operating conditions, the sulfur species are transformed by hydrodesulfurization (HDS) reactions. However, the basic nitrogen compounds also contained in the gas oils compete with sulfur compounds for the HDS reactions^{5,6}. Indeed, catalysts used in HDT are sulfide-based catalysts and the basic nitrogen compounds are absorbed on catalyst active sites,

hence inhibiting sulfur molecules hydrogenation. Hydrodenitrogenation (HDN) is performed to remove these nitrogen compounds but neutral nitrogen compounds are known to be refractory to HDN⁷. Hence, detailed characterization of sulfur and nitrogen compounds in the gas oils and HDT effluents is a key step to improve the operating conditions of the HDT processes^{8,9}.

Fourier transform ion cyclotron resonance mass spectrometry (FT-ICR MS) provides unsurpassed resolution and mass accuracy, particularly important for analysis of complex molecular mixtures¹⁰⁻¹². Using FT-ICR MS, the many nitrogen compounds contained in gas oils can be detected and their molecular formula are unequivocally determined providing molecular identification and relative intensities according to the alkylation level of the compound¹³⁻¹⁶. For its part, MS/MS is used to provide structural characterization of the compounds. However, depending on ionization source employed, different families of heteroatomic compounds can be prioritized. Important work has been done to assess the contribution of different ionization techniques¹⁷. Electrospray ionization (ESI) is very specific, sensitive and particularly well suited to the characterization of molecules containing nitrogen. On the opposite, APPI source is less sensitive to polar compounds¹⁸. ESI is widely used for polar compounds ionization¹⁹⁻²¹. It is based on a proton transfer mechanism. Positive ion mode ESI(+) ionizes basic nitrogen compounds as $[M+H]^+$ ions while negative ion mode ESI(-) ionizes neutral nitrogen molecules as $[M-H]^-$ ions.

The quality of FT-ICR MS characterization is highly reliant on sample ionization and ion transfer conditions. However, few studies have focused on the influence of the sample ionization conditions over molecular ionization, except on ion suppression in positive electrospray²² or on response towards GCxGC-SCD (Sulfur Chemiluminescence Detector)²³. Both conditions (ionization and ion transfer) have

Table 1: Properties of gas oils samples used in this study. (-) indicates that analysis was not available. The ASTM standard used for analysis is mentioned for each property.

Sample	Type (*)	Geographical origin, hydrotreatment feed or mix compositions	Density at 15°C (g/cm ³) <i>Ref. method: ASTM D4052</i>	Total sulfur (ppm) <i>Ref. method: ASTM D2622</i>	Total nitrogen (ppm) <i>Ref. method: ASTM D4629</i>	Basic nitrogen (ppm) <i>Ref. method: ASTM D2896</i>	Boiling point range (°C) <i>Ref. method: ASTM D86</i>	Total aromatics (%) <i>Ref. method: ASTM D2269</i>
GO 1	SRGO	Middle-East	0.8541	13555	115	47	219-386	28.9
GO 2	SRGO	North Europe	0.8665	7044	254	100	258-396	29.9
GO 3	SRGO	North Europe	0.8878	10979	350	129	244-396	37.5
GO 4	SRGO	Middle East	0.8484	8892	114	42	221-381	23.1
GO 5	SRGO	-	0.8491	4189	96	48	186-392	25.3
GO 6	LCO	-	0.9130	9496	928	91	199-386	59.8
GO 7	LCO	Lybia	0.9413	11074	1170	49	248-390	61.4
GO 8	LCO	-	0.9035	2231	496	141	166-304	69.4
GO 9	GOCK	-	0.8501	14796	893	404	148-358	-
GO 10	GOCK	-	0.8581	12723	838	390	163-371	28.6
GO 11	GOCK	-	0.8640	15314	1200	449	173-375	34.0
GO 12	GOCK	-	0.8813	24270	1260	569	188-401	35.0
GO 13	EBGO	-	0.8712	1248	1719	855	199-429	38.3
GO 14	FBGO	-	0.8522	344	195	121	180-359	37.4
GO 15	MIX	65% SRGO (GO5)+35% LCO (GO6)	0.8708	6400	380	63	189-391	-
GO 16	MIX	67% GOCK +33% LCO	0.8576	14004	988	436	151-351	32.8
GO 17	HDT	GO 16	0.8585	190	93	14	184-383	34.8
GO 18	HDT	GO 16	0.8591	261	140	23	187-386	35.5
GO 19	MIX	55% SRGO (GO5) +30% LCO (GO7) +15% GOCK (GO11)	0.8828	14162	586	122	218-390	39.6
GO 20	HDT	GO 19	0.8678	2813	464	107	211-388	38.7
GO 21	HDT	GO 19	0.8617	626	205	38	209-387	36.9
GO 22	HDT	GO 19	0.8691	3656	723	330	210-389	39.4
GO 23	MIX	50% LCO+50% LCO	0.9310	9125	925	98	206-368	67.0

(*): SRGO = Straight Run Gas oil; LCO = Light Cycle Oil; GOCK = Coker Gas Oil; EBGO = gas oil from ebullating bed reactor; FBGO = gas oil from fixed bed reactor; MIX = blended gas oil.

never been simultaneously and exhaustively evaluated to find optimal conditions. Therefore, the introduction of a Design of Experiment (DoE) methodology where many factors need to be assessed might be relevant, as recently mentioned in other studies with similar multi-factorial optimization goals^{24,25}. The aim of this work is to provide a molecular characterization of nitrogen compounds for several gas oil cuts with different origins. To our knowledge, it is the first work comparing gas oils produced from different industrial processes in order to extract similarities or differences between them at the molecular level. In a first step, DoEs will be used to find optimal ionization and ion transfer conditions for gas oils cuts resulting from different industrial processes. Then, all gas oils cuts will be analyzed considering 6 replicates by ESI(+/-)-FT-ICR MS as a way of evaluating the analysis repeatability. After checking figures of merit, molecular compositions of the samples will be compared to each other. As an application to this method optimization, a feed and two hydrotreatment (HDT) effluents will be also compared to follow HDT pathway of denitrogenation process⁹.

MATERIAL AND METHODS

23 gas oils samples were selected according to their process origin and compositions: 5 SRGO, 3 LCO, 4 GOCK, 1 EBGO, 1 FBGO and 4 blends. 5 HDT effluents were also selected, along with their corresponding original crude oils. Information

about their geographic origin (if available), physical characteristics and elementary compositions are given in Table 1. The ionization of the samples was a key point in this study. Therefore, several conditions of dilution, mix of solvents and amount of added additive were tested by using a design of experiment. All HPLC-MS grade solvents (Toluene, Methanol, Acetonitrile and Dichloromethane) were purchased from VWR (Fontenay-sous-Bois, France).

Design of Experiment (DoE)

DesignExpert[®] software version 10 (Stat-Ease, Minneapolis, MN, USA) was used to build the DoE. A custom design was chosen so that response surface was studied with definitive screening design and reduced quadratic model. The experiment design involved 13 runs and was applied to 4 different samples including 1 SRGO, 1 LCO, 1 GOCK and 1 HDT (samples GO 5, 7, 11 and 21 in Table 1). The aim was to find common conditions for all types of gas oils to best represent gas oils database diversity. DoE experiments were performed in both ionization modes so that the total number of DoE performed was eight. Details about conditions, response factors and plan choices are described below. Table 2 summarizes all conditions tested in DoEs depending on the selected ionization mode.

Table 2: Conditions selected to build the DoE for each ionization mode. LL=Lower Limit, UP=Upper Limit

Type	ESI(+)	ESI(-)
Ionization conditions	% dilution v/v (LL:0.1, UL:1)	
	Solvents ratios %Toluene/%Methanol v/v (LL:75/25, UL:25-75)	
	% additive v/v (LL:0.05, UL:0.15)	
Ions transfer conditions	Spray voltage kV (LL:3.5, UL:4.5)	Spray voltage kV (LL:2.5, UL:3.5)
	Tube lens V (LL:70, UL:140)	Tube lens V (LL:-70, UL:-140)
	Capillary voltage V (LL:30, UL:50)	Capillary voltage V (LL:30, UL:50)

Upper level (UL) and lower level (LL) of each factor are also provided (in brackets), an intermediate level between these two being also considered for each factor.

FT-ICR MS measurements

Mass spectrometry analyses were carried out using an LTQ FT Ultra FT-ICR MS instrument (ThermoFisher Scientific, Bremen, Germany) equipped with a 7 T superconducting magnet and ESI source (ThermoFisher Scientific) used in positive and negative modes. Mass range was set to m/z 98–1000. Mass spectra were acquired considering 4 μ scans, 70 scans, a resolution set to 200,000 (transient length of 1.6 s) at $m/z=300$ (center of average GO mass distribution) and time-domain signals (transients) was recorded in .DAT file format (ThermoFisher Scientific). AGC (Automatic Gain Control) target value was set to 5×10^5 charges, and ion injection time varied between few ms to 100 ms depending on the considered sample. Ionization and ion transfer conditions were optimized considering different GO samples as part of the DoE: tube lens, capillary and spray voltages were varied. Syringe infusion pump flow rate was set to 5 μ L/min. No nebulizing gas was used. Mass scale calibration tuning was first performed using Calmix[®] (ThermoFisher Scientific). External mass calibration was then performed with a custom sodium formate clusters solution (sodium formate from VWR, Fontenay-sous-Bois, France) covering the entire selected mass range (90–1000 Da).

Data Processing

Data were processed using several software tools. First, the Peak-by-Peak[®] software (Spectroswiss, Lausanne, Switzerland) was used to conditionally-average the obtained transients. Then phase correction function was determined using Autophaser^{®26} (part of AutoVectis package, Spectroswiss). The DPAK apodization algorithm was employed, with 2 zero pads and third order of fit. Absorption-mode FT mass spectra were then loaded into Peak-by-Peak[®] for signal-dependent noise thresholding and peak picking²⁷. Output text files were then submitted to the in-house software written in Matlab (called Kendrick Inside, IFPEN) to get access to the identification of the different compounds, molecular formula assignment and for Kendrick and Van Krevelen diagrams²⁸. Molecular formula assignment conditions were the following ones: $C_{0-50}H_{0-100}O_{0-2}N_{0-2}S_{0-2}$ with maximum content of heteroatoms in one molecular formula set to 3 and maximum error between theoretical and experimental masses set to 5 ppm in the first round of attribution. Iterative mass recalibration was then processed on the mass spectra

with Peak-by-Peak[®] considering 1 N1 family with a maximum mass error set to 1 ppm²⁹. The workflow used is described in Figure S1, Supplementary Information.

The 1 N1 compound family (i.e. where “1” refers to protonated molecules and “N1” indicates that these protonated compounds have only one atom of nitrogen) was assumed to contain all elementary basic or neutral nitrogen. Relative Intensities Normalized to Nitrogen Content (RINNC) were obtained by calculating relative intensities for each 1 N1 compound (peak intensity divided by the sum of intensities from all 1 N1 peaks). These relative intensities were then multiplied by the amount of basic nitrogen in ppm (ASTM D2896) in the sample (or neutral nitrogen for ESI(-) data, ASTM D2896 and ASTM 4629).

Two values were particularly useful: double bond equivalent index (DBE) that corresponds to the aromaticity of the molecule and the number of carbon atoms contained in the molecule. Thus, all families were assigned according to their DBE values. As example in the case of neutral nitrogen compounds, pyrroles-type compounds have DBE indexes between 3 and 5, indoles-type compounds, between 6 and 8, carbazoles-type compounds between 9 and 11, benzocarbazoles-type compounds between 12 and 14, dibenzocarbazoles-type between 15 and 17, and benzonaphthocarbazoles-type between 18 and 20. Compounds with DBE higher than 20 were classified as “others”. The number of carbon atoms was considered to identify the alkylation level of the molecule.

RESULTS AND DISCUSSION

Sample ionization and ions transfer conditions were first optimized with a design of experiment (DoE). Basic and neutral nitrogen speciation was then performed with ESI source considering positive and negative modes for all 23 gas oils samples. Lastly, relative intensities of compounds from nitrogen families for one feed and two different HDT process effluents were compared by monitoring DBE and variations of number of carbon atoms throughout hydrotreatment.

Optimization of sample ionization and ions transfer conditions using DoE

Before proceeding with gas oil sample analysis, optimization of both sample ionization and ion transfer conditions were required. Considering a number of factors that could be optimized, varying all these factors one by one to study the individual impact of these changes would have been very time-consuming. In order to avoid that, a design of experiment in a three-level factor configuration was considered. The main challenge was to design a DoE with few runs which could be performed within a day due to technical constraints and, more important, to prevent possible day-to-day variation.

Several ionization conditions were chosen to be tested including level of dilution, solvent ratios and amount of additive added to improve ionization. Different value ranges were selected depending on the considered ionization mode (see Table 2). A previous study has shown that relative abundance of 1 N1 class compounds was the highest for low crude oil dilutions levels²². Preliminary tests were carried out to choose appropriate dilution solvents and thus focus DoE on the most interesting value ranges. Dichloromethane,

acetonitrile, toluene and methanol were tested in different ratios. Mix of toluene (*Tol*) and methanol (*MeOH*) seemed to be more suited allowing the ionization of key molecular ions from nitrogen species. Acetic acid and ammonium hydroxide were used as additives either to facilitate protonation of basic nitrogen compounds or to facilitate deprotonation of neutral nitrogen compounds. Low levels of additives were tested as high concentration of formic acid (providing similar behavior as acetic acid) could lead to important decrease of 1 N1 class abundance in ESI(+) mode due to ion suppression^{20,22}.

A similar optimization methodology was applied to ions transfer conditions with preliminary tests to guide the selection of factors range values. Three conditions were selected in the DoE: spray voltage, tube lens and capillary voltage. To evaluate the efficiency of ionization and ion transfer conditions, three responses were studied focused on nitrogen compounds description: the number of identified peaks of interest (1 N1 family), the *m/z* ranges within identified peaks of interest and the sum of intensities from peaks of interest.

Since design of experiment methodology has never been published for ESI-FT-ICR MS data, a fast and basic DoE was applied. The aim of DoE was to screen the different factors using response surface methodology (RSM) and assess DoE relevance for high-resolution mass spectrometry data. In summary, the DoE was required to include six quantitative factors with three levels evaluated by three different responses. Experimental plans classically used in literature such as Box-Bekhen designs^{24,30} or factorials designs²⁵ required too many runs for this study considering the constraint of performing all analysis within one day. As a consequence, a definitive screening design was chosen including 13 runs. Since a definitive screening design includes few runs to perform full analysis of effects and interactions, it was preferred to give clues on the most relevant conditions.

Each of the selected responses were described by RSM^{25,30,31} creating individual models based on auto-selection adjusted R^2 criterion. Then, multi-responses optimization was performed using desirability function^{24,32} to select optimal conditions of sample ionization and ions transfer. Response criterions had equal weight and were set to be maximized, while factors were set to be within selected ranges. For example, given GO 5 sample (Table 1) analyzed in ESI(-) mode, the modeling of number of 1 N1 identified peaks response was performed via auto-selection based on adjusted R^2 criterion. The F-value of this model was 95.75 meaning that there was only 0.03% chance that the model was not statistically significant (ANOVA statistical analysis). The signal to noise ratio was assessed by the *Adequate precision* criterion equal to 32 in this case (a notional minimum corresponding to 4). Finally, the quality of the model was evaluated by comparing an adjusted R^2 equal to 0.98 to a Predicted R^2 equal to 0.96, with a difference of less than 0.2 required to consider a good model quality. Similar results were obtained for other responses.

3D surface responses are plotted in Figure 1 as a function of dilution level (in %) and *Tol-MeOH* ratio (in %), other factors being considered as fixed. Considering all responses, RSM gave an optimal solution with a desirability function of 0.999 for a dilution level of 0.5%, a toluene-methanol ratio of 25%-75%, 0.15% of additive, capillary voltage set to -50 V, tube lens set to -140 V and spray voltage set to 3.5 kV. This optimal solution has been also observed with other screening designs developed on samples GO 7, 11 and 21 with very

reasonable desirability values. As a consequence, this set of conditions was validated as a common optimal one for ESI(-). Figure 1D shows the evolution of the desirability function as a function of two factors.

A similar optimization methodology has been applied to ESI(+) data. Results obtained for the GO 21 sample in ESI(+) mode are detailed here. The model F-value was 94.5 so that there was 0.16% chance that the model was not statistically significant. Signal to noise ratio was 30. Adjusted R^2 value was 0.98 and predicted one was 0.94 in agreement with the less than 0.2 difference criterion. Considering all responses, RSM gave different solutions, the best one having a desirability of 0.984. This optimal solution suggested a level of dilution equal to 1, a 25%-75% toluene-methanol ratio, 0.05% of additive, capillary voltage set to 50 V, tube lens set to 110 V and spray voltage set to 3.7 kV. This optimal solution was also observed for samples GO 5, 7 and 11 with very reasonable desirability. In conclusion, this set of conditions was validated as common optimal one for ESI(+).

To sum up, using ESI(-) mode, samples were diluted to 0.5% in 25-75 *Tol-MeOH* and 0.15% of ammonium hydroxide was added. Spray voltage was set to 3.5 kV, tube lens to -140 V and capillary voltage to -50 V. In ESI(+) mode, samples were diluted to 1% in 25%-75% *Tol-MeOH* with 0.05% of acetic acid. Spray voltage was 3.7 kV, tube lens was 110 V and capillary voltage was set to 50 V.

Repeatability evaluation

The repeatability of FT-ICR MS acquisitions was evaluated by measuring six different replicates. 6 different vials were prepared for each gas oil and they were analyzed as six technical replicates. This method development was oriented towards nitrogen compounds description, so repeatability evaluation focused on nitrogen pseudo-concentrations obtained for the several nitrogen families. Relative standard deviations (RSD) of families pseudo-concentrations identified over six replicates were calculated. Families whose pseudo-concentrations were inferior to 2 ppm for ESI(+) and ESI(-) were discarded. Mean RSD of all families for each gas oil samples are available (Table S1 in Supplementary Information). In summary, maximal RSD values are lower than 7% for both ionization modes and mean RSD values are lower than 2.5% which is a very good figure of merit in the field. From our point of view, these results allow us to consider a good repeatability over several analysis of the samples. As a comparison, RSD repeatability values reported in literature by Pereira *et al.*³³ has been evaluated between 5 and 18% for N1 class in ESI(+) mode and between 2 and 7% in ESI(-) mode with only 2 replicates considering heteroatomic classes. Consequently, RSD values obtained here were considered to be low enough to enable further comparisons between gas oils samples. Reproducibility was not evaluated in this study since data was acquired by the same operator, with the same instrument and in the same laboratory.

Positive electrospray ionization: focus on basic nitrogen species

Basic nitrogen species were characterized by using ESI(+)-FT-ICR MS ionized as $[M+H]^+$ ions. Each sample was analyzed in optimized conditions and data were processed as described in material and methods section.

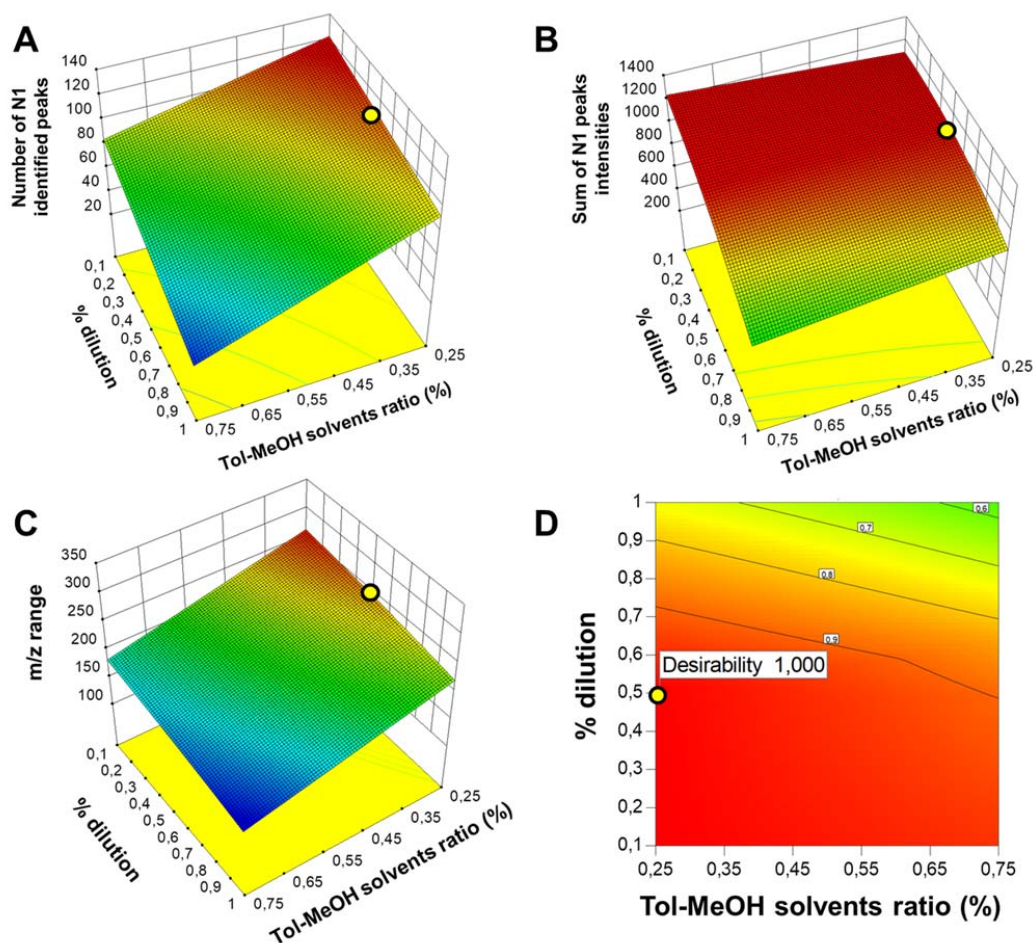


Figure 1: 3D Surface plots of every response as a function of different factors for GO 5 sample in ESI(-) mode and RSM desirability function. (A) Number of 1 N1 identified peaks response 3D surface plot as a function of the level of dilution and Toluene-Methanol solvents ratio. (B) Sum of 1 N1 peaks identified intensities response 3D surface plot as a function of the level of dilution and Toluene-Methanol solvents ratio. (C) m/z range response 3D surface plot as a function of the level of dilution and Toluene-Methanol solvents ratio. (D) Desirability function of RSM obtained for GO 5 in ESI(-) mode. Yellow dots correspond to optimum points.

About 30,000 to 40,000 peaks were identified for each sample. Initial peak resolution was 250,000 at m/z 300 with a drastic increase to 700,000-900,000 after phase correction (absorption mode FT spectral representation), highlighting the assets of the proposed data processing approach. Differences between theoretical and experimental masses (mass error) were lower than 100 ppb. An example of mass spectra between m/z 100 and m/z 500 obtained from Sample GO 3 is shown in Figure 2A. Figure 2B shows the DBE vs carbon numbers plot generated for the 1 N1 class from this spectrum. It represents the evolution of DBE as a function of number of carbon atoms showing distribution of identified peaks depending on their aromaticity (DBE) and alkylation levels (number of carbon atoms). The different families are identified depending on DBE values and dotted lines in the plot define limits for this identification. Molecular structures representing key compounds are also represented in the figure, such as pyridines (part of DBE family from 4 to 6 also including anilines and tetrahydroquinolines, THQ), quinolines (DBE family from 7 to 9) and acridines (DBE family from 10 to 12).

Figure 3A shows the relative abundance distribution of heteroatomic classes identified according to the type of gas oil

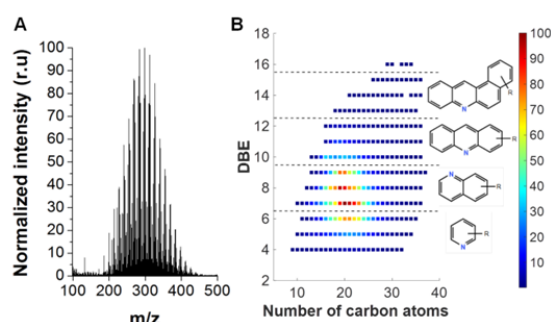


Figure 2: (A) ESI(+)-FT-ICR MS spectrum from Sample GO 3. (B) DBE= $f(C\#)$ plot generated from this mass spectrum considering 1 N1 class.

analyzed extracted from mass spectra. The results presented in this section should be considered from a qualitative point of view showing the diversity of matrix according to the considered gas oils. Indeed, as method optimization was focused on N1 family ionization maximization, other families cannot be considered from a pseudo-quantitative point of view and thus the complete additivity of the method cannot be verified, especially for low abundance classes.

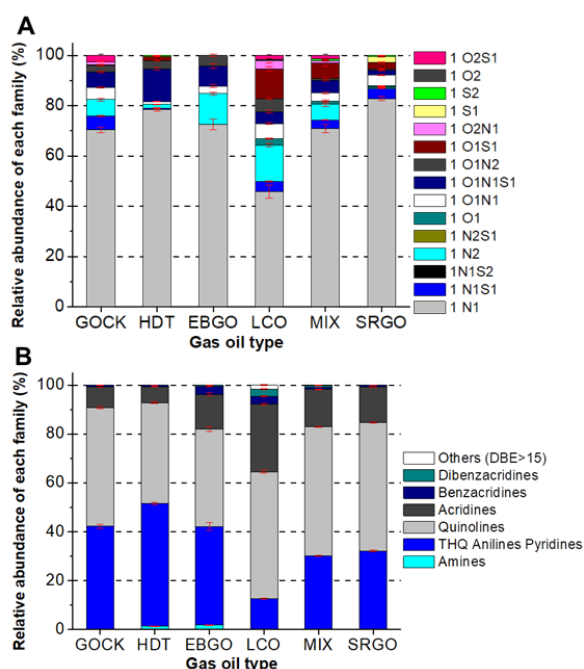


Figure 3: (A) Relative abundance of heteroatomic classes identified in ESI(+) depending on type of gas oil (5, 6, 9, 13, 15 and 20 were randomly selected). (B) Relative abundance of 1 N1 compounds families identified as a function of the gas oil type in ESI(+). The standard deviation error bars colored in red have been added on both figures.

Six different gas oils (GO 5 [SRGO], GO 6 [LCO], GO 9 [GOCK], GO 13 [EBGO], GO 15 [MIX] and GO 20 [HDT]) were selected for further comparisons. MIX sample was composed of GO 5 (SRGO) and GO 6 (LCO). 1 N1 class (containing only one atom of nitrogen, and so on for the other classes), 1 N2, 1 N1S1, 1 O1N1S1 classes were mainly identified for all samples. As expected, 1 N1 class showed the highest relative abundance³⁴ for most of samples as ESI(+) is highly sensitive towards basic nitrogen compounds¹. LCO sample which is quite heavy and have high heteroatoms contents revealed higher abundances in multi-heteroatomic compounds such as 1 N2 (13%), 1 O1S1 (13%), 1 O1N2 (5%) or 1 O2N1 (5%). On its part, EBGO sample is obtained using vacuum residue hydrocracking and has thus low sulfur content compared with other samples. Hence no heteroatomic class containing sulfur was significantly abundant. GOCK sample showed relatively high contents of multi-heteroatomic compounds, especially sulfur-containing ones such as 1 N1S1 (5%), 1 N1O1S1 (6%) and 1 O2S1 (4%). MIX sample composed of both LCO and SRGO gas oils has logically intermediate characteristics between their initial relative abundance profiles. When looking more thoroughly the composition of the MIX, some gaps can be evidenced between the MIX and the SRGO/LCO distributions, especially for low abundance classes such as 1 O2N1 or 1 S1 (see Figure S2 in Supporting Information). Indeed, as this method was optimized only for 1 N1 class (which is here the major class of interest), some ionization suppression could take place for low abundance classes to favor intentionally 1 N1 ionization. Lastly, the HDT sample was collected at intermediate hydrotreatment severity so it is not surprising that heteroatomic classes such as 1 O1N1S1, 1 O1N1 or 1 O1S1 still remained observed. Considering only 1 N1 family, differences were also spotted within samples and were related

to their properties, shown in Figure 3B. LCO sample has high aromatic content (see aromatics content in Table 1) and contained more compounds with high DBE, such as acridines, benzacridines, dibenzacridines or even higher molecular structures. On the other side, the selected SRGO sample has intermediate aromatic content and contained more compounds with lower DBE, like tetrahydroquinolines anilines pyridines or quinolines, as well as GOCK sample. EBGO sample contained almost all families, which is characteristic of its origin. Indeed, VR cracking induces formation of lighter species and some heavier species might not be converted. HDT sample led to highest content of low DBE-compounds due to the hydrogenation of nitrogen compounds during hydrotreatment. Thus, EBGO and HDT samples contained amines that were produced along with nitrogen compounds hydrogenation. MIX sample composition looked more alike SRGO sample than LCO sample, as composition was about 65% SRGO-35% LCO. In such complex matrix, there are some obvious ionization competition mechanisms between basic nitrogen compounds. Especially, we can suspect here an ionization competition between Acridines and THQ Anilines Pyridines. The pKa of these species are quite close (5.6 VS 4.4, 4.6 and 5.2) which mean that they should be equally protonated and thus ionized. However, the alkylation of these compounds is a major factor when assessing ionization efficiency. Indeed, the addition of alkyl groups on the core structures could increase the protonation efficiency and thus the ionization yield of a family. Here, the THQ Anilines Pyridines family in MIX sample is highly alkylated as the distribution of the number of carbon atoms for this family is centered over C20, that is an average of about 10 to 15 additional carbon atoms compared to the core structures of these molecules. On the opposite, the Acridines family is poorly alkylated (centered over C17 that is 3 additional carbon atoms) in the MIX sample (see Figure S3 in Supporting Information). Then, we can assume that the THQ Anilines Pyridines are more easily ionized compared to Acridines in SRGO sample in the MIX. This could explain these unexpected high abundances of THQ Anilines Pyridines compared to theoretical abundances based on MIX proportions. However, these differences represent about 5% of the relative intensities in the MIX sample.

Negative electrospray ionization: focus on neutral nitrogen species

Negative electrospray ionization was used to get access to neutral nitrogen species. Mass spectra and their corresponding DBE vs carbon numbers plot are available in Figures S4 and S5 in Supplementary Information. In line with what has been done for ESI(+) data, the relative abundance of heteroatomic classes identified in ESI(-) were also studied (see Figure 4A). ESI(-) mode allowed us to observe a wide range of compounds. However 1 N1 class was less ionized than already shown in previous studies considering for example GOCK samples^{34,35}. Oxygen compounds, especially for SRGO and MIX, were well ionized as seen elsewhere²⁰. The sum of relative abundances of 1 O1 and 1 O2 families reached 60% for SRGO and 40% for MIX. HDT sample did not contain any O2-compounds because they are very easily removed during hydrotreatment as well as EBGO sample, which also went through oxygen removal during VR hydrocracking. Common families were identified both by ESI(+) or ESI(-) such as 1 N1O1, 1 N1S1, 1 O1S1 in similar proportions, probably

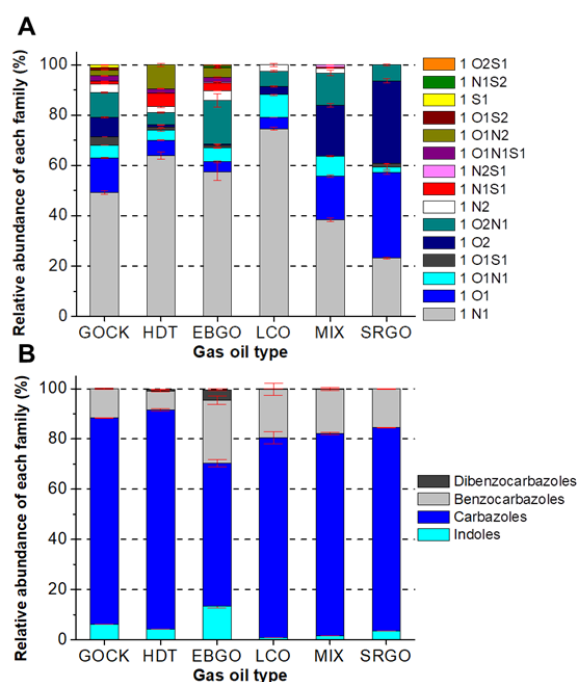


Figure 4: (A) Relative abundance of heteroatomic classes identified in ESI(-) depending on gas oil type. (B) Relative abundance of 1 N1-compounds families identified as a function of the type of GO in ESI(-). The standard deviation error bars colored in red have been added on both figures.

due to the amphoteric character of the molecules contained in these families. LCO sample showed the highest proportion of 1 N1 compounds as this sample has the highest content in neutral nitrogen. The relative abundance of N1-compounds families identified according to the type of gas oil was plotted in Figure 4B. EBGO sample contains the highest proportions of high-DBE compounds such as dibenzocarbazoles or benzoocarbazoles but also low-DBE compounds such as indoles, as expected as EBGO cracking produces both light and heavy compounds. Surprisingly, dibenzocarbazoles and benzonaphthocarbazoles that are the heaviest neutral compounds were not detected in LCO sample whereas it was the heaviest sample. The high proportion of low-DBE compounds (Indoles and Carbazoles) in SRGO samples was expected, as well as in HDT and GOCK samples, according to their light character (referring to their low contents of heavy aromatics compounds). MIX proportions were in agreement with theoretical composition (see Figure S6 in Supporting Information).

Hydrotreatment process monitoring: feed and effluents analysis

Samples GO 20 and 21 are two products from the hydrotreatment of the GO 19 sample. They were collected at different hydrotreatment severity level. Sample GO 20 was collected at low HDT severity (highest nitrogen content, 20% HDN conversion) and sample GO 21 at high HDT severity (lowest nitrogen content, 65% HDN conversion). In the following part, feed will refer to sample GO 19, HDT 1 to sample GO 20 and HDT 2 to sample GO 21. Catalytic tests were carried out using the same catalyst, same pressure and same temperature, the only difference between samples being the severity level. Figure 5A shows the evolution of the relative intensity normalized to nitrogen content (RINNC) within

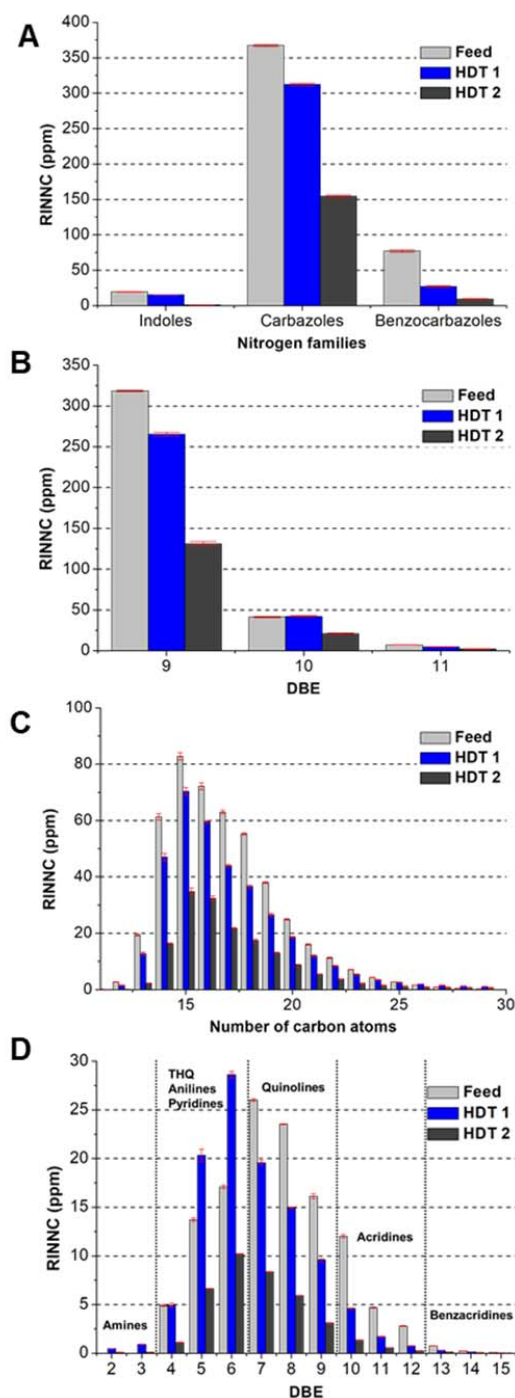


Figure 5: (A) Comparison of nitrogen compounds relative intensity normalized to nitrogen content (RINNC) evolution within different neutral families. (B) Comparison of RINNC according to DBE values for carbazoles. (C) Evolution of RINNC as a function of number of carbon atoms for Carbazoles family. (D) Evolution of RINNC as a function of DBE for basic nitrogen compounds families. The standard deviation error bars colored in red have been added on both figures. The standard deviation error bars colored in red have been added on all figures.

neutral nitrogen families for the 3 samples (Feed, HDT 1 and HDT 2). These intensities can be directly related to the severity level of hydrotreatment. Indeed, the RINNC within each family decrease slightly as the hydrotreatment severity increases. More consequent decrease was observed for HDT 2

in comparison to HDT 1. However, it can be stated that 150 ppm of carbazoles remained in sample after deep hydrotreatment that corresponds to almost half of the initial concentration of carbazoles, validating the well-known refractory character of these molecules^{36,37}. The evolutions of RINNC for carbazoles molecules for each possible DBE (9, 10 and 11) were different according to DBE value as seen in Figure 5B. Carbazoles with a DBE value of 10 were revealed to be the most refractory as 50% were still remaining in HDT 2, whereas only 40% and 30% remained in HDT 2 for DBE 9 and DBE 11 respectively. Besides, when considering the DBE 9-10-11 carbazoles family (Figure 5C), the evolution of RINNC over the number of carbon atoms shows that highly poly-alkylated carbazoles (starting from C14) were much more refractory than carbazoles (C12) or mono (C13) alkylated carbazoles. These reactivity differences might be explained by steric hindrance created by high-degree of alkylation. It may inhibit efficient catalyst action on carbazoles core molecule, especially if methyl groups surround nitrogen molecules³⁸. The evolution of RINNC of the compounds over DBE was also assessed to follow hydrotreatment mechanisms for some basic molecules (Figure 5D). Acridines molecules, with initial DBE from 10 to 12 are known to be converted into less aromatic products with DBE equals to 6, 5, 3 and 2³⁹. This was in accordance with increases or decreases of RINNC of the compounds identified. The RINNC of DBE 10-Acridines in feed was about 12 ppm and decreased to less than 5 ppm and 1 ppm for HDT 1 and HDT 2 respectively. On the other hand, the RINNC of DBE 6-THQ Anilines Pyridines, DBE 5-THQ Anilines Pyridines and DBE 3 and 2-Amines⁴⁰ increased in sample HDT 1 from 17 to 29 ppm, from 14 to 21 ppm and from about 0 to 1 ppm respectively. However this last concentration is close to repeatability limit so this variation should be considered carefully. The increase in DBE 6-THQ Anilines Pyridines and DBE 3 and 2-Amines can also be attributed to carbazoles conversion, present with high content in the feed (about 320 ppm before hydrotreatment and only 170 ppm removed during). Indeed, hydrogenation of DBE 9-carbazoles compounds induces the formation of DBE 6-Indoles and then to basic species detected in ESI(+) as basic nitrogen compounds such as DBE 6-THQ Anilines Pyridines and DBE 3 and 2-Amines^{41,42}. Hydrotreatment mechanisms for carbazole and acridine molecules are available in Supplementary Information in Figure S7, as well as the evolutions of RINNC for the different basic nitrogen compounds and as a function of the number of carbon atoms in Figure S8.

CONCLUSION

Gas oils extracted by a simple distillation from crude oils (i.e SRGO), derived from very different industrial processes (i.e LCO, GOCK, EBGO and FBGO), mixed blends or hydrotreated effluents were analyzed using ESI(+/-)-FT-ICR MS. DoE was applied for the first time to ESI-FT-ICR MS experiment in order to obtain optimal sample ionization and ions transfer conditions for each ionization mode. The statistical analysis of six technical replicates for each of the 23 crude oils gave good results in terms of repeatability allowing rightful comparison between the samples. Thus, an optimized and repeatable analytical method was developed to characterize gas oils samples from all possible origins using

ESI FT-ICR MS. In order to validate this method, results of FT-ICR MS were related to the macroscopic properties of the crude oils (elementary contents of sulfur, nitrogen, boiling points and density) from a heteroatomic class point of view but also within the class of interest i.e. 1 N1. Then, comprehensive information on hydrotreatment was obtained by following the relative intensities normalized to nitrogen contents (RINNC) differences between one feed and two different effluents. The well-known refractory character of some compounds has been highlighted and evolutions of their DBE and number of carbon atoms towards hydrotreatment have been followed. Because relative intensities have been considered in this study, future works will focus on the improvement of quantification towards more absolute concentration aspects. This could lead thereafter to an even finer monitoring of hydrotreatment reactions and consequently to a better modeling of these industrial processes. In this article, development was only oriented towards 1 N1 families, leading to sensitive and repeatable method. It is obvious that other families such as 1 N1S1, 1 N2 or 1 N1O1 are of high interest. However, classical data processing methods are not at this time efficient enough to simultaneously explore all interesting compounds between different heteroatomic families. For this purpose, chemometric approaches (i.e. multivariate data analysis tools) appear promising. Specifically, data fusion methods would allow combining data information from several heteroatomic classes and go deeper into processes characterization and comprehension.

ASSOCIATED CONTENT

Supporting Information

Data processing workflow used, RSD repeatability values for each gas oil, Comparison of experimental and theoretical MIX heteroatomic classes relative abundances for ESI(+), Comparison of theoretical and experimental MIX compositions for basic nitrogen families, Comparison of the distribution of relative intensity according to the number of carbon atoms of the molecules for the THQ Anilines Pyridines and Acridines for MIX sample, ESI(-)-FT-ICR MS spectra and Kendrick Plot of 1N1 family for SRGO Sample 3, Comparison of theoretical and experimental MIX compositions for neutral nitrogen families, HDN mechanisms of Acridines and Carbazole compounds according to DBE evolution throughout hydrotreatment, Basic nitrogen compounds evolution throughout hydrotreatment (PDF)

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Notes

The authors declare no competing financial interest.

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REFERENCES

- (1) Marshall, A. G.; Rodgers, R. P. *Petroleomics: chemistry of the underworld. Proceedings of the National Academy of Sciences of the United States of America* **2008**, *105*, 18090–18095.
- (2) BP Statistical Review of World Energy 2017 **2017**.

- (3) *Petroleum Formation and Occurrence*; Tissot, B.P.; Welte, D.H., Eds., 2., nd ed. 1984. Softcover reprint of the original 2nd ed. 1984; Springer Berlin: Berlin, 2013.
- (4) Rabarihoela-Rakotovo, V.; Diehl, F.; Brunet, S. Deep HDS of Diesel Fuel: Inhibiting Effect of Nitrogen Compounds on the Transformation of the Refractory 4,6-Dimethyldibenzothiophene Over a NiMoP/Al₂O₃ Catalyst. *Catal Lett* **2009**, *129*, 50–60.
- (5) Nguyen, M. T. Support acidity effects of NiMo sulfide catalysts in hydrodenitrogenation of quinoline, indole and Coker Gas Oil: Thesis manuscript (France), 2016.
- (6) Sau, M.; Basak, K.; Manna, U.; Santra, M.; Verma, R. P. Effects of organic nitrogen compounds on hydrotreating and hydrocracking reactions. *Catalysis Today* **2005**, *109*, 112–119.
- (7) Ishihara, A.; Wang, D.; Dumeignil, F.; Amano, H.; Qian, E. W.; Kabe, T. Oxidative desulfurization and denitrogenation of a light gas oil using an oxidation/adsorption continuous flow process. *Applied Catalysis A: General* **2005**, *279*, 279–287.
- (8) Nguyen, M.T.; Pirngruber, G.; Chainet, F.; Albrieux, F.; Tayakout-Fayolle, M.; Geantet, C. Molecular level insights into straight run/coker gas oil hydrodenitrogenation by Fourier Transform Ion Cyclotron Resonance Mass Spectrometry. *Energy Fuels* **2019**, *33*, 3034–3046.
- (9) Wiwel, P.; Knudsen, K.; Zeuthen, P.; Whitehurst, D. Assessing Compositional Changes of Nitrogen Compounds during Hydrotreating of Typical Diesel Range Gas Oils Using a Novel Preconcentration Technique Coupled with Gas Chromatography and Atomic Emission Detection. *Ind. Eng. Chem. Res.* **2000**, *39*, 533–540.
- (10) Marshall, A. G.; Hendrickson, C. L. Fourier transform ion cyclotron resonance detection: principles and experimental configurations. *International Journal of Mass Spectrometry* **2002**, *215*, 59–75.
- (11) Marshall, A. G.; Hendrickson, C. L.; Jackson, G. S. Fourier transform ion cyclotron resonance mass spectrometry: A primer. *Mass spectrometry reviews* **1998**, *17*, 1–35.
- (12) Marshall, A. G.; Rodgers, R. P. Petroleomics: The next grand challenge for chemical analysis. *Accounts of chemical research* **2004**, *37*, 53–59.
- (13) Cho, Y.; Ahmed, A.; Islam, A.; Kim, S. Developments in FT-ICR MS instrumentation, ionization techniques, and data interpretation methods for petroleomics. *Mass spectrometry reviews* **2015**, *34*, 248–263.
- (14) Marshall, A. G. Fourier transform ion cyclotron resonance mass spectrometry. *Accounts of chemical research* **1985**, *18*, 316–322.
- (15) Smith, D. F.; Podgorski, D. C.; Rodgers, R. P.; Blakney, G. T.; Hendrickson, C. L. 21 Tesla FT-ICR Mass Spectrometer for Ultrahigh-Resolution Analysis of Complex Organic Mixtures. *Analytical chemistry* **2018**, *90*, 2041–2047.
- (16) Nikolaev, E. N. Some notes about FT ICR mass spectrometry. *International Journal of Mass Spectrometry* **2015**, *377*, 421–431.
- (17) Gutiérrez Sama, S.; Farenc, M.; Barrère-Mangote, C.; Lobinski, R.; Afonso, C.; Bouyssi re, B.; Giusti, P. Molecular Fingerprints and Speciation of Crude Oils and Heavy Fractions Revealed by Molecular and Elemental Mass Spectrometry: Keystone between Petroleomics, Metallopetroleomics, and Petrointeractomics. *Energy Fuels* **2018**, *32*, 4593–4605.
- (18) Purcell, J. M.; Hendrickson, C. L.; Rodgers, R. P.; Marshall, A. G. Atmospheric pressure photoionization fourier transform ion cyclotron resonance mass spectrometry for complex mixture analysis. *Analytical chemistry* **2006**, *78*, 5906–5912.
- (19) Hughey, C. A.; Rodgers, R. P.; Marshall, A. G. Resolution of 11 000 Compositionally Distinct Components in a Single Electrospray Ionization Fourier Transform Ion Cyclotron Resonance Mass Spectrum of Crude Oil. *Anal. Chem.* **2002**, *74*, 4145–4149.
- (20) Hughey, C. A.; Rodgers, R. P.; Marshall, A. G.; Qian, K.; Robbins, W. K. Identification of acidic NSO compounds in crude oils of different geochemical origins by negative ion electrospray Fourier transform ion cyclotron resonance mass spectrometry. *Organic Geochemistry* **2002**, *33*, 743–759.
- (21) Purcell, J. M.; Rodgers, R. P.; Hendrickson, C. L.; Marshall, A. G. Speciation of nitrogen containing aromatics by atmospheric pressure photoionization or electrospray ionization fourier transform ion cyclotron resonance mass spectrometry. *Journal of the American Society for Mass Spectrometry* **2007**, *18*, 1265–1273.
- (22) Ruddy, B. M.; Hendrickson, C. L.; Rodgers, R. P.; Marshall, A. G. Positive Ion Electrospray Ionization Suppression in Petroleum and Complex Mixtures. *Energy Fuels* **2018**, *32*, 2901–2907.
- (23) Muller, H.; Adam, F. M.; Panda, S. K.; Al-Jawad, H. H.; Al-Hajji, A. A. Evaluation of quantitative sulfur speciation in gas oils by Fourier transform ion cyclotron resonance mass spectrometry: Validation by comprehensive two-dimensional gas chromatography. *Journal of the American Society for Mass Spectrometry* **2012**, *23*, 806–815.
- (24) Buratti, C.; Barbanera, M.; Lascaro, E.; Cotana, F. Optimization of torrefaction conditions of coffee industry residues using desirability function approach. *Waste management (New York, N.Y.)* **2018**, *73*, 523–534.
- (25) D'Archivio, A. A.; Di Pietro, L.; Maggi, M. A.; Rossi, L. Optimization using chemometrics of HS-SPME/GC–MS profiling of saffron aroma and identification of geographical volatile markers. *Eur Food Res Technol* **2018**, *244*, 1605–1613.
- (26) Kilgour, D. P. A.; Nagornov, K. O.; Kozhinov, A. N.; Zhurov, K. O.; Tsybin, Y. O. Producing absorption mode Fourier transform ion cyclotron resonance mass spectra with non-quadratic phase correction functions. *Rapid communications in mass spectrometry : RCM* **2015**, *29*, 1087–1093.
- (27) Zhurov, K. O.; Kozhinov, A. N.; Fornelli, L.; Tsybin, Y. O. Distinguishing analyte from noise components in mass spectra of complex samples: Where to cut the noise? *Analytical chemistry* **2014**, *86*, 3308–3316.
- (28) Islam, A.; Cho, Y.-J.; Ahmed, A.; Kim, S.-H. Data Interpretation Methods for Petroleomics. *Mass Spectrometry Letters* **2012**, *3*, 63–67.
- (29) Kozhinov, A. N.; Zhurov, K. O.; Tsybin, Y. O. Iterative method for mass spectra recalibration via empirical estimation of the mass calibration function for Fourier transform mass spectrometry-based petroleomics. *Analytical chemistry* **2013**, *85*, 6437–6445.
- (30) Zielinski, A. A. F.; Haminiuk, C. W. I.; Beta, T. Multi-response optimization of phenolic antioxidants from white tea (*Camellia sinensis* L. Kuntze) and their identification by LC–DAD–Q–TOF–MS/MS. *LWT - Food Science and Technology* **2016**, *65*, 897–907.
- (31) Bezerra, M. A.; Santelli, R. E.; Oliveira, E. P.; Villar, L. S.; Escalera, L. A. Response surface methodology (RSM) as a tool for optimization in analytical chemistry. *Talanta* **2008**, *76*, 965–977.
- (32) Viacava, G. E.; Roura, S. I.; Ag ero, M. V. Optimization of critical parameters during antioxidants extraction from butterhead lettuce to simultaneously enhance polyphenols and antioxidant activity. *Chemometrics and Intelligent Laboratory Systems* **2015**, *146*, 47–54.
- (33) Pereira, R. C. L.; Simas, R. C.; Corilo, Y. E.; Vaz, B. G.; Klitzke, C. F.; Schmidt, E. M.; Pudenzi, M. A.; Silva, R. M. C. F.; Moraes, E. T.; Bastos, W. L. *et al.* Precision in Petroleomics via Ultrahigh Resolution Electrospray Ionization Fourier Transform Ion Cyclotron Resonance Mass Spectrometry. *Energy Fuels* **2013**, *27*, 7208–7216.

(34) Mapolelo, M. M.; Rodgers, R. P.; Blakney, G. T.; Yen, A. T.; Asomaning, S.; Marshall, A. G. Characterization of naphthenic acids in crude oils and naphthenates by electrospray ionization FT-ICR mass spectrometry. *International Journal of Mass Spectrometry* **2011**, *300*, 149–157.

(35) Xiaobo, C.; Yibin, L.; Jin, W.; Honghong, S.; Chaohe, Y.; Chunyi, L. Characterization of nitrogen compounds in coker gas oil by electrospray ionization Fourier transform ion cyclotron resonance mass spectrometry and Fourier transform infrared spectroscopy. *Applied petrochemical research* **2014**, *4*, 417–422.

(36) Wiwel, P.; Hinnemann, B.; Hidalgo-Vivas, A.; Zeuthen, P.; Petersen, B. O.; Duus, J. Ø. Characterization and Identification of the most Refractory Nitrogen Compounds in Hydroprocessed Vacuum Gas Oil. *Ind. Eng. Chem. Res.* **2010**, *49*, 3184–3193.

(37) Zeuthen, P.; Knudsen, K. G.; Whitehurst, D. D. Organic nitrogen compounds in gas oil blends, their hydrotreated products and the importance to hydrotreatment. *Catalysis Today* **2001**, *65*, 307–314.

(38) Shin, S.; Sakanishi, K.; Mochida, I.; Grudoski, D. A.; Shinn, J. H. Identification and Reactivity of Nitrogen Molecular Species in Gas Oils. *Energy Fuels* **2000**, *14*, 539–544.

(39) Girgis, M.J.; Gates, B.C. Reactivities, reaction networks, and kinetics in high-pressure catalytic hydroprocessing. *Ind. Eng. Chem. Res.*, **1991**, *30*, 2021–2058.

(40) Klein, G. C.; Rodgers, R. P.; Marshall, A. G. Identification of hydrotreatment-resistant heteroatomic species in a crude oil distillation cut by electrospray ionization FT-ICR mass spectrometry. *Fuel* **2006**, *85*, 2071–2080.

(41) Nagai, M.; Masunaga, T.; Hanaoka, N. Hydrodenitrogenation of carbazole on a molybdenum/alumina catalyst. Effects of sulfiding and sulfur compounds. *Energy Fuels*, **1988**, *2*, 645–651.

(42) Stern, E.W. Reaction networks in catalytic hydrodenitrogenation. *Journal of Catalysis*, **1979**, *57*(3), 390–396.

